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Development of a dual MCP framing camera for high energy x-rays [a)]

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Recently developed diagnostic techniques at LLNL require recording backlit images of extremely dense imploded plasmas using hard x-rays, and demand the detector to be sensitive to photons with energies higher than 50 keV[1,2]. To increase the sensitivity in the high energy region, we propose to use a combination of two MCPs. The first MCP is operated in low gain regime and works as a thick photocathode, and the second MCP works as a high gain electron multiplier. We tested concept of this dual MCP configuration and succeed to to obtain the detective quantum efficiency 3.9% for 59 keV x-ray photons.

I. INTRODUCTION

X-ray framing cameras based on proximity-focus micro-channel plates (MCP) have been playing an important role as diagnostics of inertial confinement fusion experiments [3]. Most of the current x-ray framing cameras consist of a single MCP, a phosphor, and a recording device (e.g. CCD or photographic films). This configuration is successful for imaging x-rays with energies below 20 keV. In this single MCP configuration, the MCP works as both photocathode and electron multiplier. To have enough optical output from the phosphor, the MCP has to be operated with electron multiplication gain of 500 ~ 2000. Therefore detective quantum efficiency (DQE) above 20 keV is severely reduced due to the large gain differential between the top and bottom of the plate for these volumetrically absorbed photons [4]. One approach to reduce this DQE reduction is to separate photocathode from the electron multiplier. We propose to stack two MCPs and operate the first one in low gain regime and use as a thick photocathode, and use the second MCP as an electron multiplier to have enough optical output from the phosphor.

II. DQE AND NOISE FACTOR

Quantum efficiency (QE), which is defined as the number of detected events per number of input quanta, is a commonly used metric for estimation of the statistical noise of the obtainable image when the output of the single detection event has smaller variance. For detectors which has broad pulse height distribution (PHD), DQE is the quantity of interest [5]. The definition of the DQE is

$$DQE \equiv \left(\frac{SNR_o}{SNR_i}\right)^2, \qquad (1)$$

where SNR_o and SNR_i are signal-to-noise ratio of output and input respectively. By using DQE and number of incident photons per resolution element (N_i) expected signal-to-noise ratio of the image can be evaluated as,

$$SNR_o = \sqrt{DQE \times N_i} \quad (2).$$

Another useful metric is a noise factor defined as[6]

$$NF = 1 + \frac{\sigma^2}{\langle\xi\rangle^2} \qquad (3),$$

where $<\xi>$ is the mean and σ is the standard deviation of the PHD. When noise from other sources (e.g. multiplicative noise due to non-uniform sensitivity over detection area or statistical fluctuation of background exposure) are small, the DQE can be expressed as [7]

$$DQE = \frac{QE}{NF} \qquad (4).$$

III. EXPECTED PHD OF SINGLE MCP

The statistical uncertainty of an avalanche multiplication process is usually modeled by Pólya or Furry statistics [8]. When an avalanche stream is started from a single electron and the number of collision in the MCP pore is large, the PHD can be approximated by a negative exponential [9],

$$\left.\frac{dP(\xi)}{d\xi}\right|_{avalanche} = \frac{1}{\langle\xi\rangle}\exp\left(-\frac{\xi}{\langle\xi\rangle}\right) \qquad (5),$$

where ξ and $<\xi>$ are the gain and the expected value of the gain.

Another source of PHD broadening is a depth dependent gain of the electron multiplication[10]. The electron multiplication started from depth x from the entrance is,

$$\xi(x) = \xi_0^{\frac{L-x}{L}} \qquad (6),$$

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where ξ_0 is the nominal gain of the stream started on x= 0, L is the total thickness of the MCP. The PHD determined by this depth dependence is

$$\left.\frac{dP(\xi)}{d\xi}\right|_{depth} = \left|\frac{dP(x)}{dx}\right| \cdot \left|\frac{dx}{d\xi}\right|$$

$$= \begin{cases} \dfrac{\mu L}{1-e^{-\mu L}} \dfrac{1}{\ln(\xi_0)} e^{-\mu L\left(1-\frac{\ln(\xi)}{\ln(\xi_0)}\right)} \xi^{-1} & when \quad 1 \le \xi \le \xi_0 \\ 0 & otherwise \end{cases}$$

where μ is the linear absorption coefficient of the MCP. For hard x-ray ($\mu L < 1$), this equation is simplified

$$\left.\frac{dP(\xi)}{d\xi}\right|_{depth} = \begin{cases} \dfrac{1}{\ln(\xi_0)} \xi^{-1} & when \quad 1 \le \xi \le \xi_0 \\ 0 & otherwise \end{cases} \quad (7).$$

The expected PHD was estimated by numerically convoluting eq.6 and 7 (Fig. 1). When the averaged electron multiplication is high, the effect of the depth dependent gain is dominant and the PHD shows long tail with ξ^{-1} dependence. We evaluated the noise factor with using this numerically generated PHD. Fig. 2 shows the calculated noise factor versus the averaged pulse gain in the MCP. The simulated noise factor is approximated by an empirical fitting

$$NF(\langle\xi\rangle) = 1 + \left[1 + \left(1.17 \ln(\langle\xi\rangle)\right)^2\right]^{0.5}, \quad (8)$$

and it has minimum = 2 when the MCP is operated near unity gain. To have a strong enough signal to in harsh neutron induced background environment[11], an MCP based neutron detectors has to be operated with $\langle\xi\rangle$ = 500 ~ 2000. Therefore the expected noise factor of cameras with single MCP configuration is 8~10.

In order to obtain enough DQE with MCP gain ~1000, we propose to stack two MCPs. The first low-gain MCP works as thick x-ray photocathode. The 2nd MCP amplifies the electron stream. To confirm advantage of this concept, we assembled a test module and measured the QE and the PHD of the single and dual MCP setup.

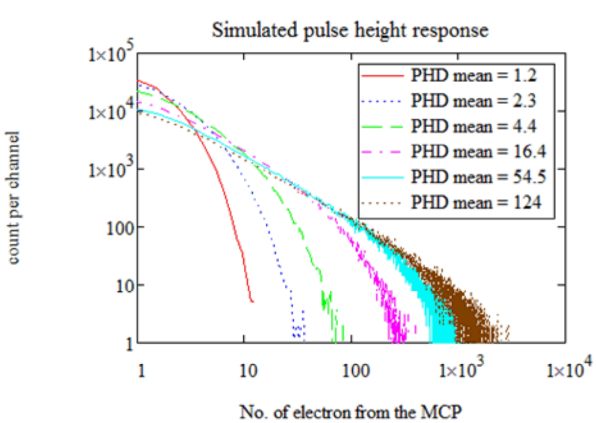

FIG. 1.Expected PHD was numerically calculated by convoluting eq. 6 and 7. Total number of event is set to 10^5.

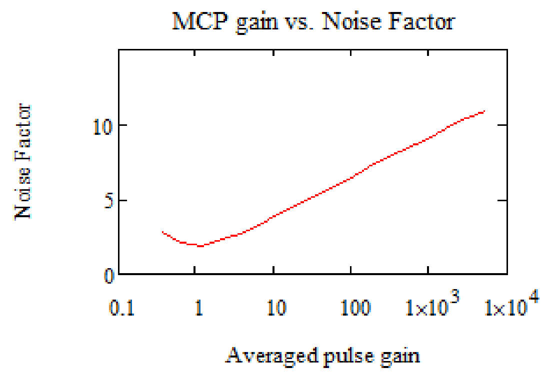

FIG. 2. Noise factor calculated from the simulated PHDs. It is possible to reduce the noise factor due to depth dependent gain by using MCP on low gain.

II. EXPERIMENT

Fig. 2 shows the experimental setup. The MCP was irradiated by 59 keV x-ray from the radioactive source (^{241}Am,10μCi) 45mm from the surface of the MCP. Low energy emission lines from the Am241 source (13.9, 26.3, 33.2, and 43.4 keV) was filtered by an aluminium filter (3.88mm thick, also works as vacuum window). X-ray photons are converted to electrons in the MCP. After multiplication in the MCP, electrons are accelerated to 3keV and hit the P46 phosphor ($Y_3Al_5O_{12}$:Ce) coated on the fiber optic face plate. The optical output from the phosphor was detected by the photo-multiplier tube (PMT: Hamamatsu R329-02, bias: 1.1 kV). The PMT signal was amplified by a charge sensitive amplifier (ORTEC 113), shaped (ORTEC 460) and recorded by the multi-channel analyzer (MCA: ORTEC TRUM PCI 8K). The dynamic range of the pulse height recording system (the saturation level divided by minimum detectable threshold) is limited to about 100. To extend the dynamic range, we performed measurement twice with different gain setting (0.15 ~ 40 pC and 1.2 ~400 pC range) and splice those spectra on 20pC. Background counts from the PMT, the MCP, and the direct x-ray excitation on phosphor was measured separately and subtracted from the raw data.

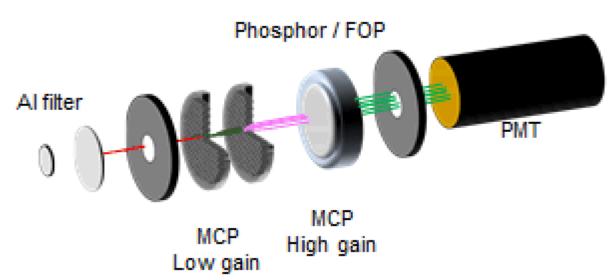

FIG. 3. Experimental setup

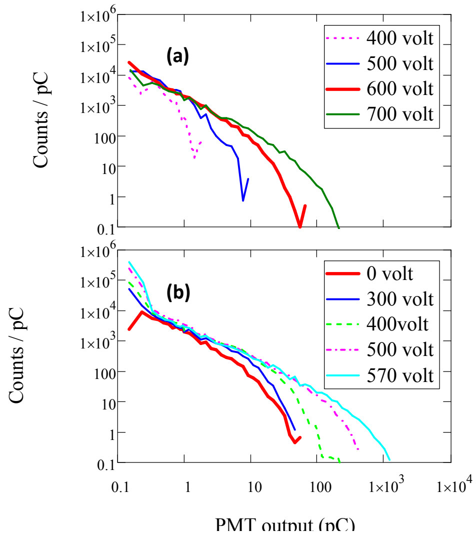

FIG. 4. Experimantally obtained pulse height distribtuon: (a) single MCP 460µm thick, (b) dual MCP 460µm + 460µm.

Fig. 4 shows the PHD obtained in this experiment. When single MCP (thickness L:460µm, pore diameter d: 10µm) is operated in low gain (Fig. 2(a)), the PHD is close to the negative exponential and standard deviation of the PHD is close to the mean value. When we increase the MCP gain by applying higher bias voltage, the depth dependent gain effect becomes significant and the PHD turns into $<\xi>^{-1}$ dependence. Fig. 2(b) shows the result of dual plate. We changed the bias voltage given to the 1st MCP (Vs) from 0 ~ 570V and the 2nd MCP was operated with 600V bias. When Vs = 0 volts, all the events are dominated by x-ray detection on the 2nd MCP and the observed PHD was almost identical to that o single plate with the same voltage.

We measured PHD of 800µm thick single MCP as well. Fig. 4 shows the QE and DQE of the single MCP configuration as a function of the bias voltage.

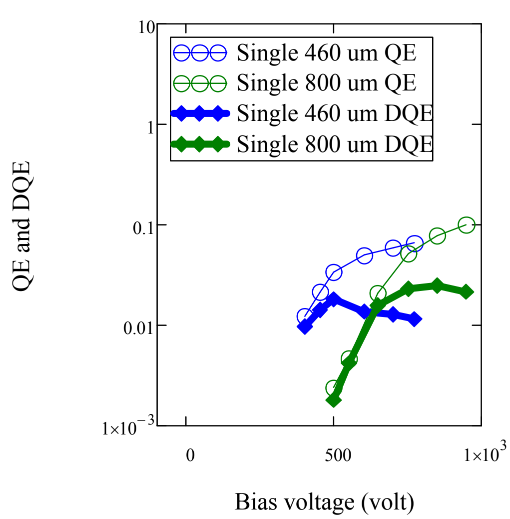

Fig. 5. Measured QE and DQE of the single MCP

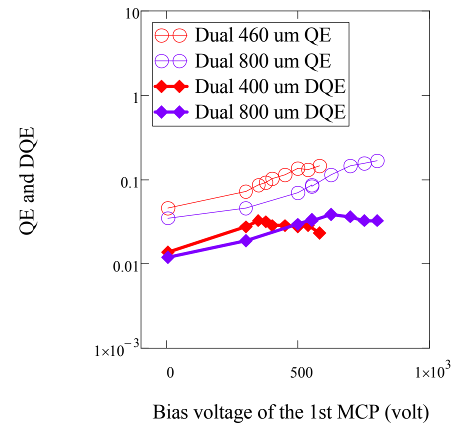

Fig. 6. Measured QE and DQE of the dual MCP

The observed DQE is departing the QE on high gain side due to the depth dependent gain effect. When the nominal MCP gain is 10^3 (the nominal PMT signal ~18pC/event), the observed DQE was 1.1% (2.2%) for 460µm (800 µm) thick plate. Fig. 6 shows the result of the dual MCP configuration. When no bias voltage is given to the 1st plate (Vs = 0), the result was consistent to the single MCP with 600V bias. When Vs is near the turn on voltage of the MCP, highest DQE was observed. When Vs is higher than the turn on voltage, DQE went down due to the depth-dependent gain effect on the 1st MCP. When nominal MCP gain is 10^3, the observed DQE was 2.8% for the 460 µm thick (3.6% for the 800 µm thick) 1st MCP.

III. DISCUSSION

By using the dual MCP configuration, the noise factor of the system was reduced and the DQE was successfully increased by factor 3 compared to commonly used 460µm thick single MCP configuration. However, reduced QE was experienced when the gain of the 1st MCP was set low. We believe this voltage dependent QE is due to termination of the electron stream on the first collision with the pore wall (end up with zero multiplication which follows Poission statistics). If that is the case, the QE can be significantly improved by reducing the L/d ratio of the 1st MCP because it is possible to accelerate the electron to a higher energy with keeping low overall multiplication gain [6].

IV. ACKNOWLEDGMENTS

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